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RESEARCH ARTICLE

Heat Flux for Welding Processes: Model for Laser Weld

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ABSTRACT

An accurate and physically suitable heat flux model is required to represent the welding process. Experimentally established processes are referred. A well-established model in heat flux representation is the double ellipsoid model of Goldak. It provides non-symmetry of the front and rear heat to the electrode as given by Lindgren. Though this is a good representation, it can be simplified to a conical heat model for the molten metal with a Gaussian heat input. This combination is suited for laser beam welding process as the heat beam focuses through a conical collate. Proposals for improved linear combinations of two fluxes are defined and different distributions of heat fluxes are compared. It also includes the evaluation of Gaussian distribution of heat flux to explain process capability.
Keywords: Welding, Heat flux, Double ellipsoid model, Gaussian heat input, Laser beam.

1. INTRODUCTION

There are several metal joining processes like arc welding, plasma welding, laser or electron beam or hybrid laser-arc welding. In all these phenomena, the applied heat flux is used to join the materials under exposure by means of melting and solidification. Rather, the analysis of any weld process involves complex material melting, fluid flow, phase changes and metallurgical effects. Thermo-mechanical modeling of heat sources is widely attempted. In this development, heat source assumptions with point and line sources are evolved initially and weld arc process is represented pertaining to the temperature field distribution. Further, arc phenomenon analysis extended to area and volumetric heat source models overcome the problems limited by temperature distribution field [1-4].

The area and volume of metal exposed by the weld process gives phase transformation of the molten metal due to the applied thermal heat flux load at melting point. Heat source models development further aid in the modeling of the accurate weld process [5-7]. Heat Affected Zone (HAZ) and Fusion Zone (FZ) are to be accurately modeled to obtain the correct temperature changes which further affect the residual stresses and deformations. The challenges in implementing the material properties and temperature dependent modeling were attempted. Thermo-mechanical modeling of weld processes has progressed in analytical models and was validated by experimentation using various processes significantly. In this study, a review of some possible geometrical features has been addressed. Gaussian distribution which is an established distribution to laser weld processes is studied from the definition of process capability. Their efficiency in processes like laser and electron beam is higher when compared with arc welding due to high power density with respect to narrow focused heat flux and high speed process which will further result in low distortion and residual stresses.

The present study aimed to investigate the appropriate heat flux model representation for laser beam weld process model. This study also gives a combined Gaussian and frustum model; Gaussian for the heat flux above the metal surface and frustum to represent the molten metal (keyhole) below the surface. Both have a common circular surface on the metal surface where the beam falls before melting.

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Finite element methods [8-10] are attempted to obtain close approximation. In this study, the definition of heat flux at different distances from the weld central line is analyzed for different shapes of heat distribution. Heat flux at the center and at any point away from the center is given. These values are important in giving load at nodes of finite element models. This data will help the researcher in providing correct heat input in simulation and modeling.

2. ANALYTICAL APPROACH

In the welding processes approach, arc or laser beam phenomena involve a heat source with moving molten pool representation with temperature field distribution over the volume under exposure. Laser weld process is represented as Gaussian beam source, when the laser beam is at top and near to conical type during the keyhole formation process. The present study gives the outline of standard heat flux model definitions along with the associated mathematical equations.

2.1. Line flux

For a spot welding process all the heat functions are located at a point. The analysis is shown in equation (2.1) to (2.25). Welding is done by providing heat energy as in equation (2.1).

$$Q = VI\eta \tag{2.1}$$

where V is the voltage, I is the current and η is the efficiency of resistance welding process. In this example, heat is provided by electric supply as in an electric weld process. If the Heat Affected Surface (HAS) is defined as area, then heat flux,

$$q = Q/\mathrm{area} \tag{2.2}$$

For a circular area assuming that all the heat is given at a spot, like in spot welding, q can be related as shown in equation (2.3).

$$q = Q = VI\eta \tag{2.3}$$

2.2. Transient load and heat flow

If the heat is given for a period of t seconds uniformly and continuously, q can be given in terms of power as in equation (2.4),

$$Q(t) = q(t) * t.\, q = Q/t \tag{2.4}$$

Welding heat available at the weld bead may not be constant initially as there will be time for temperature stabilization due to losses. It is stable over a period of time and subsequently, when power is switched off from the source, flux will ramp down as it gathers heat from the surroundings until it equalizes to that of the surroundings. Ramp up model of heat energy can be taken as a surface heat input. This is an approximation which can be substantiated by measurements of temperatures over the surface. Addition of filler heat can be added as an impulse.

At every position of the weld point, heat increases up to a given time and then a constant heat is supplied. If filler is used, then filler heat is used at this point as a pulse and after an incremental time, the heat input reduces to zero as the electrode moves on to the next position. In this study, heat is considered as static working on a circular surface.

2.3. Cylindrical flux

Assuming the surface area of radius a where heat provided is circular, heat flux per unit area is given in equation (2.5)

$$q = {}^{Q}\!/_{(\pi a^2)} \tag{2.5}$$

It is constant at every point on the surface. This heat flow may not be representing the known welding processes. This model represents heat flow when temperature is low and when there is no melting.

2.4. Conical flux

A conical heat flux has a maximum heat at the center point say q (0). Then the total heat is related as,

$$Q = {}^{1}\!/_{3} * \pi\, q(0) * a^2 \tag{2.6}$$

$$q(0) = 3 * {}^{Q}\!/_{(\pi * a^2)} \tag{2.7}$$

$$q(r) = q(0)(1 + {}^{r}\!/_{a}) \tag{2.8}$$

where, a is the radius of the surface area where the heat is acting on the material. Gas weld brazing is close to this when the nozzle is of small diameter and the flame is touching the material at the maximum diameter.

2.5. Flux frustum

In many processes the heat flow volume forms a frustum with a top (r_t) and a bottom radius (r_b) at the bottom. The volume of the flux is given by,

$$Q = q(0) * {(r - r_b)}/{(r_r - r_b)} \quad (2.9)$$

The above equation is obtained by subtracting the top cone of radius (r_t) from the bigger cone formed by the larger radius (r_b)

2.6. Heat flux as a Gaussian distribution

This distribution has special importance as it is proven that many manufacturing processes follow a Gaussian or normal distribution. Gaussian heat distribution is used by earlier researchers. A Gaussian distribution is plotted with population density which is the heat flux density at y axis and population standard deviation σ at x axis, centered about the mean of heat flux (μ). When σ = 1 and μ=0, the distribution becomes a normalized distribution. For a standard normal function, P(z) relates the probability of occurrence for $x < z$ which is given by the heat flux area as,

$$q(r) = q(0)e^{-cr2} \quad (2.10)$$

where q(r) is the surface flux at radius r(W/m^2), q(0) is the maximum flux at the center of heat source, r =0 (W/m^2) is the heat flux radius, radial distance from the center and C is the parameter for flux shape, if r_f is the radius of plume.

$$r_f > r \quad (2.11)$$

$$c = {r^2}/{r_f^2} \quad (2.12)$$

$$q(0) = {VI\eta}/{\pi r_f^2} \quad (2.13)$$

The total input power of welding system is,

$$Q = VI\eta \quad (2.14)$$

r_f is generally larger than r, as heat spreads and heat loss occurs which reduces the effective heat zone radius r and thus

$$r_f => r \quad (2.15)$$

Since a Gaussian distribution relates the process capability, in this study, the use of Gaussian distribution is analyzed with respect to the effect of process spread as explained by the number of standard deviation and the specification levels.

2.7. Ellipsoid a volume heat flux model

The temperature distribution of welded parts in the HAZ and melt FZ were measured. Goldak [3] has given a double ellipsoid model which is well established and used in simulating heat flux in the steady state with no time dependence, in where the flux q is given as:

$$q(x, y, z) = \frac{6Q\sqrt{3}}{abc\pi\sqrt{\pi}} e^{-3x^2/a^2} e^{-3y^2/b^2} e^{-3z^2/c^2} \quad (2.16)$$

$$q(0) = \frac{6Q\sqrt{3}}{abc\pi\sqrt{\pi}} \quad (2.17)$$

where, a, b and c are the semi axis of the ellipsoid in x, y and z direction. The double ellipsoid model has an ellipsoid to the front and one to the rear. For dissimilar welds it may be required to use four octants with independent a, b, c values giving quadrant ellipsoid heat flux model. In this study, the semi elliptical heat flux is assumed to be present on a circular surface.

From the basic equations of ellipse, we can derive for an elliptical flux of central value q(0) and for any radius q(r). The elliptical limits are the radius of base circular area (a) on which the flux is distributed.

$$q(0) = \frac{2Q}{a\sqrt{\pi}} \quad (2.18)$$

$$q(r) = q(0) * (1 - \frac{r^2}{a^2}) \quad (2.19)$$

2.8. Heat distribution in laser weld and finite element analysis

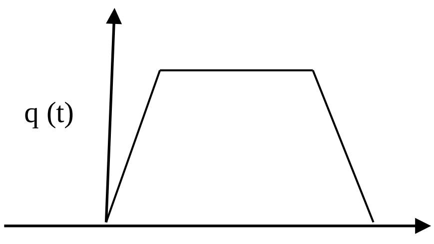

Figure 1.Constant heat flux

Figure 1 gives the Gaussian distribution for heat flux and the molten

welded zone is given by a frustum if W_g, W_f are the weighting functions. In proportionally distributing the heat flux, a linear combination of the two heat fluxes q_g, q_f results in total heat Q.

$$Q = W_g * q_g * W_f * q_f \tag{2.20}$$

This distribution gives a more realistic representation for laser and electron beam welding [3, 4]. In this study, an evaluation of W_g=W_f=0.5 was taken and compared with Gaussian and frustum distributions. The finite element analysis requires the discrete values of power at each node points. For a circular surface, a quadratic element distribution is shown in figure 2.

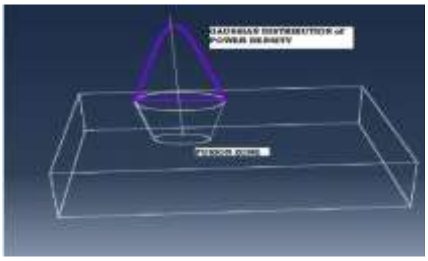

Figure 2.A heat flux model for laser beam welding

The heat transfer problem is KT = F, Here the K matrix is heat conduction matrix, T is the output temperature domain and F is the heat input vector. If the laser heat is on surface, f_s and f_v is the heat added through volume.

$$F = f_s + f_v \tag{2.21}$$

$$fs = \int_s NQds \tag{2.22}$$

The surface and the volume heat transferred is given as,

$$fs = \int_s NQds \tag{2.23}$$

where N is the shape function vector. In both the cases it is required to give the heat flux discretely at each nodal point as shown in figure 3.

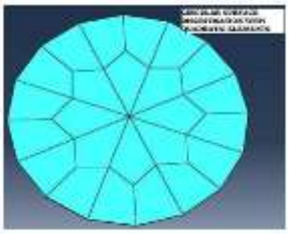

Figure 3.Quadratic elements for circular weld surface

In commercial packages the pre-processor software does this calculation. To provide the required software, a subroutine to incorporate the distribution is to be written. In this study, the heat flux is given at the centre q(0) and at any distance r, q(r) in the circular surface. Figure 4 shows the different cases of heat flux.

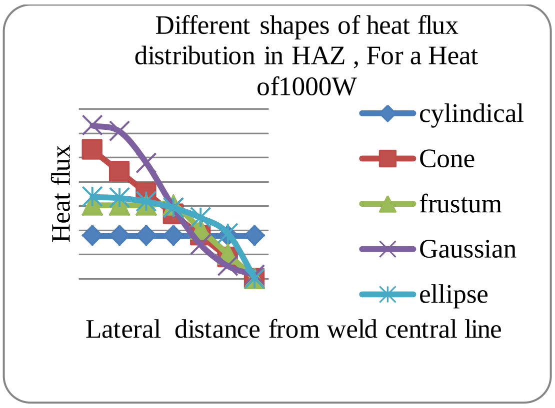

Figure 4.Heat flux models of different geometric shapes

2.9. Process representation by Gaussian distribution

The Gaussian distribution is proved to give the statistical probability distribution of manufacturing processes and their outcome. If the specified limits are Upper Specified Limit (USL) and the Lower Specified Limit (LSL), tolerance is USL-LSL. If the process is in control, the output follows a Gaussian distribution. For welding heat flux which has this distribution with standard deviation (σ), as variation along the radius and the mean (μ) equal to the heat at the center (q(0)), process capability (C_p) is defined as,

$$c_p = {(USL - LSL)}\Big/{(UCL - LCL)} \tag{2.24}$$

where the upper and lower control limits are parameters depending on the process capability. When the process capability is equal to 1, the acceptance is ∓3 σ and the process acceptance is 99.73% within specs. When C_p=2, the acceptance is ∓6 σ, which is said to be 6σ process and the rejections are in parts per million.

The process capability occurrence is studied by noting the probability of occurrence which is the area difference from the reference radial distance r to the central point. In this

study a trend line is fitted which can be used where table availability is not given.

$$\text{Probability} = 10^{-5}x^3 - 0.001x^2 + 0.051x - 0.059 \qquad (2.25)$$

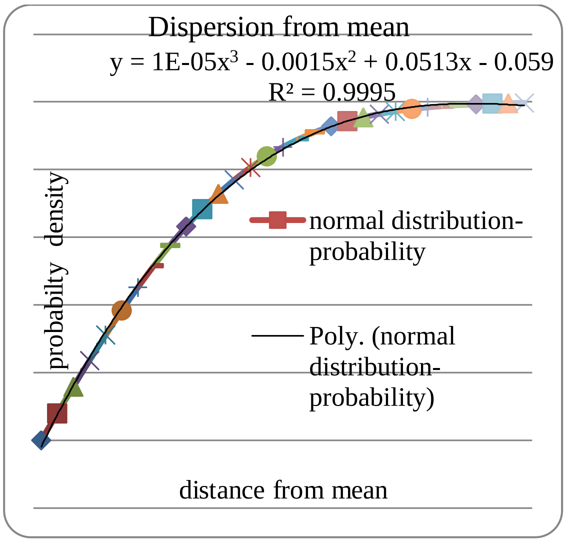

Figure 5.Probability equation for Gaussian distribution

Figure 5 gives the fitness graph. The probability values are used to evaluate the process capability for a 3σ process to a 6σ process that provides heat flux in a Gaussian geometric shape as shown in figure 6.

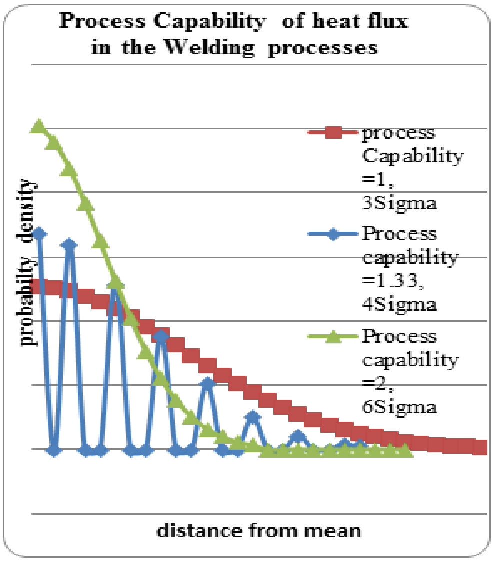

Figure 6.Process capability heat flux in the welding process

3. RESULTS AND ANALYSIS

The heat distribution of power density q(r) for Q= 1000W power acting on a circular surface of radius a=3 mm is calculated for all cases. Different heat flux models are compared in figure 4. A sharp q(0) is desired which acts on a smaller radius. Here radius is prescribed for comparison. It is measured from experiments for real situations. A comparison of central tendency and distribution can be made. A cylindrical heat flux has uniform flux along the radius and is equal at every point on the surface. This will represent heat treatment processes where melting of metal is not required. The elliptical distribution is shallow and might represent some of the shallow welds in TIG processes. In laser and electron beam, the heat flux at the center is more predominant and a Gaussian distribution is more relevant.

The heat distribution in the heat effected zone above the metal surface and below the surface with molten fusion zone are well depicted by the Goldak ellipsoid model. It can also be extended to incorporate the difference in axis to the front and rear of the weld bead center as a double ellipsoid. However, the double ellipsoid has shallow shape and a Gaussian distribution is better suited for laser and electron beam welds, where the molten zone is represented by frustum. In figure 7, the comparison of heat flux in Gaussian, frustum and an equal weighted linear combination of the two are shown. When the heat flux is represented by a Gaussian distribution, it gives us an opportunity to obtain process capability.

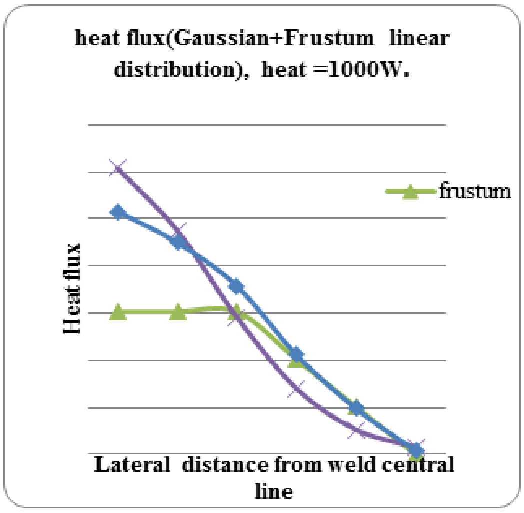

Figure 7.Linear combined heat fluxes

The study is usually obtained using the standard normal table. A cubic polynomial has been fitted which has a fit with R^2 = 0.999 as shown in figure 5. This equation may be used when table is not available. Using the probability values the process capability of

different values of standard deviation are shown. The flux shape may have a capability of 3σ with 99.73% heat within the HAZ that is about .3% failure. A 6σ capability will have 3 ppm (parts per million) or .0003% of heat, not being in HAZ.

4. SUMMARY

Different geometric models of heat flux are given with analytical solutions for a circular heat face. The ellipsoid model was found to be shallower and may not represent the laser welding process. A new linear combination of Gaussian and frustum heat models is proposed which is a better representation for sharp central heat input and deep welds. The Gaussian heat flux model can also be used to give a process capability value which will be an evaluation of the process used.

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